

# Reality — an emerging representation of the world

MARTIN A. GREEN\*

*Perimeter Institute for Theoretical Physics,  
31 Caroline St. N., Waterloo, Ontario, N2L 2Y5, Canada*

Some unique source — the world,  $\mathcal{W}$  — must underlie all the information realized in the universe throughout time. Perceived reality,  $\mathcal{R}$ , is a progressively emerging representation of  $\mathcal{W}$  in the form of the geometrical universe. Time corresponds to the process of emergence. When first represented in  $\mathcal{R}$ , information about  $\mathcal{W}$  is expressed in a non-localized, quantum manner. As the emergence proceeds, most information becomes inaccessible (entropy), supporting the robust, redundant encoding of accessible records. The past is encoded in and inferred from present records; the anticipated future will preserve present information and reveal unpredictable new information about  $\mathcal{W}$ . Emergence of the future demands non-unitary reduction of quantum states and increased Kolmogorov complexity of the quasi-classical records in terms of which the quantum states are known. Given the limited information content of records, the quasi-classical universe lacks fine details; whereas the future must be uncertain to admit new information.

## 1 INTRODUCTION

What is existence? Descartes asserted “*Cogito, ergo sum*”, linking existence to both thought and the thinker. Since thought implies formation of new memories and corresponding changes of mental state, which we perceive as existing at sequential times, Descartes’s assertion implicitly assumes time. We can neither think nor sensibly contemplate existence without an *a priori* concept of time; time is part of our nature as thinking entities.

The kernel of thought is information. When we think, we acquire, organize, remember and use information. We attribute a cause or source to this information, deeming it to be *about* something, say  $X$ . The information thus becomes the essence of  $X$ ; serves to define  $X$ . A maximal set of information about  $X$  can sensibly be identified with  $X$ . If information about  $Y$  is equivalent to a subset of information about  $X$ , then  $Y$  serves to *represent*  $X$ . If the representation is faithful, then  $Y \equiv X$ .

We categorize something as *physical* if and only if we judge that our information about the thing was acquired through use of our senses (i.e., through perception) and that the information could have been different without resulting in a contradiction. Otherwise, we attribute the information to some timeless, non-physical thing such as a mathematical object. Our bodies are intuitively physical; the melding of our body and mind enables our sensory perception of both our body and other physical things. We refer to all that is physical as the *universe*. All our information about the universe serves to define the universe. All this information is interrelated, with meaning derived from the relationships just as the words in a dictionary are defined in terms of each other.

---

\* Electronic address: [mgreen@perimeterinstitute.ca](mailto:mgreen@perimeterinstitute.ca)

Each mental state that we experience corresponds to a state of the universe that we identify as the momentary present. Acquisition of new information produces a new mental state corresponding to a new perceived state of the universe. Considerable information about the former states of the universe persists, as memories, in each new present. However, our brains have limited capacity. To optimize the ongoing utility of memories, our brains organize and selectively store information in an efficient manner, with lossy compression but ample redundancy. This entails construction of a conceptual model for the universe that involves various forms of *matter* distributed in 3-dimensional, geometrical *space* and sensibly evolving over time [1]. Time, space and matter are thus aspects of our efficient model for the universe — they aid our representation of the evolving universe, although the representation will certainly not be faithful.

Information corresponds to the properties and relationships of things. It has no intrinsic properties and thus no existence independent of the things it is about. When we develop a model of the universe as a composite of related things — which our minds do as part of their efficient memory system — some information corresponds to relationships of the components and other information to intrinsic properties of the components.

Although we each perceive the universe independently, our consensus about its properties makes us believe that the information that yields each perceived universe has an underlying source that is independent of us. The combination of *all* the information about the universe that will be potentially accessible to us over time must be attributed to a single, ultimate source. We shall call that source the *world*,  $\mathcal{W}$ . To be clear: all the information that defines each momentarily perceived universe is information about the same world. It follows that the world must be a timeless, non-physical thing. We formalize this as follows:

**Proposition 1 (World):** *The unique foundation for all information of which cognitive beings could, in principle, become aware about the past, present and future of the universe (including matter) is a definite, atemporal and enormously complex mathematical structure — the world. The world is prior to and distinct from, in an ontological sense, the universe, time, perception, and physical concepts, objects and laws.*

The thesis of this essay is summarized as follows: Perceived reality is a progressively emerging, incomplete (or unfaithful) representation of the world. Progress of time corresponds to the process of emergence of this representation. The varied mathematical and interpretational *models* we use to characterize perceived reality are structurally and conceptually distinct from the world itself. Physical laws constrain our models for perceived reality such that the models are internally consistent and coherent, and such that the modeled reality is a valid, yet limited, representation of the world. More advanced models for reality encode information about the world with greater efficiency, scope and fidelity.

Physics involves the invention, validation and use of models for perceived reality, within the context of the world. Models and physical laws formally encode structural information about our representation of the world, but they do not direct or constrain either the representation or the world. Revolutionary physics theories — Newtonian mechanics, relativity theory, quantum theory (QT), inflationary cosmology — have introduced radically different models for reality that have each proven quite useful in spite of their conceptual differences. The ongoing utility of such diverse models should make us hesitate to identify either perceived reality or any model for reality with the world. These proposals about the

world and its representation are made more explicit in section 2.

Section 3 addresses the nature of time: How can the incongruous concepts regarding time and causality of QT and general relativity (GR) be resolved to integrate these theories? How can the special status of the perceived present be understood, and be reconciled with the spacetime model of relativity theory? Given the symmetry of GR and QT under time reversal, what explains the low entropy of the early universe? More generally, why is past history known but not the future? These questions all relate to quantum uncertainty, for which we shall find a natural explanation.

To be a valid representation of the world, perceived reality must be self-consistent. Individual views of reality must be mutually compatible. In section 4 we consider how this consistency and compatibility are reflected in and constrain theoretical models. Deterministic models such as GR and QT encode and preserve already-known information about the world. Acquisition of new information necessitates quantum state reduction, and the creation of new records that are expressed through geometry and other quasi-classical descriptors of the universe<sup>1</sup>. These descriptors serve only to encode the information — they have no independent existence.

In section 5, we explore the possibility that the world is, quite simply, a smooth 4-manifold with arbitrary global connectivity but no inherent geometry, fields, or other decoration. The global topology of  $\mathcal{W}$  admits a representation with features strikingly similar to a Feynman graph. This suggests a correspondence between the topology and the virtual particles and interactions of quantum field theory. Information about the topology might thus be represented as the dynamically interacting matter and spacetime that we perceive.

The final section provides a summary and discusses implications that will be pursued in future work.

## 2 PERCEIVED REALITY

Being unique and atemporal, the world does not change, nor can temporal change be found within it. In particular, the world should not be mistaken for spacetime or a block universe [2]. However, combining Proposition 1 and the expectation that there exist *representations* of  $\mathcal{W}$  that are related by their nested information about the world leads to:

**Proposition 2 (Nature):** *Nature — perceived reality and all its generic and specific properties throughout time; the subject of all information gained from perception — is an unfaithful, progressively emerging representation  $\mathcal{R}$  of  $\mathcal{W}$ . Time corresponds to the process of emergence through which, starting with minimal information at the Big Bang, information about  $\mathcal{W}$  is cumulatively encoded in the evolving  $\mathcal{R}$ . At any given stage of emergence,  $\mathcal{R}$  holds only a small fraction of all information about  $\mathcal{W}$ ; most details of  $\mathcal{W}$  are unknowable.*

We exist, within nature, not as direct properties of  $\mathcal{W}$ , but as players in a progressively emerging representation of  $\mathcal{W}$ . While we shall generally speak of  $\mathcal{R}$  in the singular, it is by no means unique. At a minimum, each cognitive being / observer  $\mathcal{O}$  has its own variant  $\mathcal{R}_{\mathcal{O},t}$  at each perceived time  $t$ . The process of emergence of  $\mathcal{R}$ , which is perceived as passage

---

<sup>1</sup>I use *quasi-classical* to refer to observable properties of the universe about which two distinct observers should reliably agree. This need not entail the deterministic evolution of a *classical* universe.

of time, preserves (to the extent possible) that information about  $\mathcal{W}$  that has already been incorporated in  $\mathcal{R}$ , while adapting and refining  $\mathcal{R}$  to efficiently, coherently and consistently incorporate new information. Time serves to label the distinct representations, but also resides within each  $\mathcal{R}$  as the natural ordering of the accumulating historical records (and memories) from which we infer prior states of the universe.

Given Proposition 1, the generic features of both the emergence process and the representation  $\mathcal{R}$  that it yields can arise only from the structure of  $\mathcal{W}$ . These features are manifested as physical concepts, objects, and laws.

**Proposition 3 (Physics):** *Physical concepts, objects and laws characterize and constrain models for generic features of  $\mathcal{R}$  such that the models are compatible with both cognitive perception and the generic structure of  $\mathcal{W}$ . Physics arises from but does not constrain  $\mathcal{W}$ . Physical laws are conditions, within the models, under which the modeled representation  $\mathcal{R}$  will always be coherent and internally consistent.*

Each of the above Propositions has introduced a corresponding conceptual layer: (1) the world, the atemporal foundation; (2) the emergent representation of the world that is perceived reality; and (3) mathematical and interpretational models developed by physicists to characterize perceived reality. Each successive layer conveys information about the layer(s) beneath it, but has no influence on or control over the lower layer(s). We exist as active participants in the middle layer.

The mathematical and interpretational frameworks of QT and GR ensure that our layer-3 models are coherent and consistent. The Standard Model of particle physics serves to characterize generic aspects of the structure of  $\mathcal{W}$ ; whereas cosmological models characterize the global evolution of  $\mathcal{R}$  while maintaining compatibility with  $\mathcal{W}$ . When physical laws, theories and models lead us to unreasonable results, then either they do not provide valid characterization of perceived reality, or we have attempted to apply them beyond their domain of validity. Understanding the relationship of QT and GR to the lower layers will be an essential step towards resolution of unreasonable results — such as paradoxes, or issues involving singularities — and the satisfactory integration of these theories.

### 3 TIME

Issues of time have presented the greatest barrier to consistent integration of GR and QT [3, 4]. We shall explore in this section how associating time with the *process of emergence* of the representations  $\mathcal{R}$  helps elucidate time's many aspects. The scope and relationship of the classical and quantum domains will become clear, and quantum uncertainty and state reduction will be recognized as necessary in order to allow accumulation of information.

Consider the representations  $\mathcal{R}_{t_i}$  corresponding to some cognitive observer's perceived reality at her times  $t_i$ . According to Proposition 2, the advance of time corresponds to accumulation of information about  $\mathcal{W}$ , meaning that the information represented by  $\mathcal{R}_{t_2}$  is a superset of the information represented by  $\mathcal{R}_{t_1}$  whenever  $t_2 > t_1$ .<sup>2</sup> Gaining new information implies a change in mental state, which is attributed to advancing time. The nesting relationship naturally determines the direction of time.

---

<sup>2</sup>There may also be many representations of  $\mathcal{W}$  that do not involve such accumulation of information, but they will not concern us.

We each exist within a personal representation  $\mathcal{R}$  that includes ourselves and our memories — we always perceive this as the present. The nested sub-representations of  $\mathcal{R}$ , reflected in the organization of our memories, express the history of the universe that has led to our present state. Although it derives from present memories and physical records, we attribute this history to the notional past. We have no memories or records of the future, but we can anticipate the future based on our present knowledge and the requirement that present information be maximally preserved (although it may become inaccessible). Information about  $\mathcal{W}$  that is not yet incorporated into  $\mathcal{R}$  must, to avoid contradiction, be truly unknown; aspects of the future that are not mandated by compatibility with the present can only be discovered.

Accepting no observer as special, and realizing that every present is transient and will become part of history, we require that all representations  $\mathcal{R}$ , including their nested sub-representations and future representations that can only be anticipated, must have equivalent properties. Of course, a dominant requirement remains that all of these must represent different overlapping subsets of information about the same  $\mathcal{W}$ . As minor players, our perception of  $\mathcal{R}$  gives us limited access to just the most persistent information. Due to its persistence in physical records, much of this information can be accessed as required to update our memories. Our existence in each other's perceived reality mandates mutual consistency of our shared histories.

Viewed here as a synthetic concept, the past provides a robust and efficient mechanism for organizing and encoding our accumulated present information about  $\mathcal{W}$ . This suggests a new perspective on causality and determinism in which focus shifts from quantum states and spacetime events to the globally represented information. Determinism corresponds to reliable preservation of information as time advances; causality requires future representations to incorporate new information about  $\mathcal{W}$  in a manner that also ensures preservation of current information. The need to respect this orderly accumulation of information constrains our spacetime and quantum models.

Deterministic theories, such as GR and classical electrodynamics, preserve information as time advances. But such theories merely transform their dynamical model of the universe at some reference time to represent the same information in different ways at different times. Deterministic theories are thus suited to modeling of the evolving representation of already-known information in a manner that effectively decouples it from new information. Because they neither add nor remove information, they fail to distinguish the present or identify a preferred direction of time.

The unitary evolution of QT is also deterministic. Projected future quantum states and potential outcomes are based solely on presently available (or hypothetical) information. But QT, by predicting only the *probabilities* of uncertain outcomes, leaves an opening for acquisition of new information. Non-unitary quantum state reduction, which has to many people been anathema, now reveals itself as an essential process through which novel information about  $\mathcal{W}$  is added to  $\mathcal{R}$  while maintaining full compatibility with the past. Being about  $\mathcal{W}$ , this new information has no *causes* within  $\mathcal{R}$  — it is simply discovered. While the properties of  $\mathcal{W}$  limit the valid representations  $\mathcal{R}$ , there remains freedom, illustrated by the quantum Zeno effect, for cognitive acts of observers to guide the *order* in which new information is integrated into the representation. This freedom is manifested as *free will*.

Information becomes persistent through its redundant expression in the quasi-classical

universe. It is encoded in models as deterministically evolving active degrees of freedom of geometry and matter. Information that has persisted from the earliest times is now the most highly compressed and redundantly encoded in  $\mathcal{R}$ , and is thus highly accessible to diverse observers. Compression also entails entanglement, since given information is spread across many records. Cosmological models account for an enormous range of observations using just a few parameters [5]. In contrast, information that is highly localized in the geometrical model for  $\mathcal{R}$  may only be accessible to a limited set of observers and may quickly become inaccessible as the representation evolves.

With this perspective on time and perceived reality, information takes a leading role while spacetime fills a supporting role as a modeling tool. Geometrical spacetime and localized events are model-dependent abstractions, useful because they enable efficient representation of information. When that information is determined to have entered the representation in the distant past or remote locations, its encoding as geometry and matter will be necessarily coarse-grained and non-local. To represent new information as time advances, our models must become increasingly complex. Accessible information is encoded in the parameters of quasi-classical records. Redundancy makes records robust, but at the cost of making even more information inaccessible — as entropy. Advancing time increases both information and entropy. Projecting backward, one must conclude that  $\mathcal{R}$  at earlier times had progressively less information and entropy, with both eventually going to zero at the Big Bang.

## 4 THE CONSISTENT UNIVERSE

Every observer’s universe, including the past they infer from present records, must be self-consistent. Partial models of the past, based on distinct subsets of valid present records, must never imply incompatible past events. Existence of an inconsistency or incompatibility would indicate that some present information, some knowledge or memory, is not valid. For observers to share the same universe, their representations of the world must be mutually consistent. To the extent their histories overlap, they must have compatible, although generally not identical, representations of the matter content, interactions, and temporal order.

A desire to formalize this consistency and compatibility motivates the search for a single mathematical and interpretational model that accounts for core features of the representations  $\mathcal{R}$ . Physical laws, as implied by Proposition 3, are merely constraints on this model that ensure both self-consistency and compatibility with the generic structure of  $\mathcal{W}$ . A successful model will provide an efficient, highly compressed encoding of the information in  $\mathcal{R}$  about the generic and specific structure of  $\mathcal{W}$ .

We use our perceptions to test and update the details of this model. Our biological heritage causes us to do much of this subconsciously [1, 6]. Our intellectual capabilities enable us to access presently available records, including the records of experiments and past intellectual activity by ourselves (memories) and others (writings, creations, etc.), and to interpret them within our model’s framework to acquire much more elusive information. Development of a consistent model of the cosmos and its history, supported and corroborated by creatively acquired, presently accessible data, is a prime example of the sophisticated intellectual approach to acquisition and efficient representation of information

about the world.

Any given model of reality should be expected to have a limited domain of validity, even though the limits may not be obvious. Stretching a model beyond its domain, or simultaneous application of two incongruous models, can produce confusing or unreasonable results — hence the difficulty of extending QT and GR into each other’s natural domain. Given their undeniable success, we have no thought of abandoning geometrical spacetime, GR or QT for alternative models. Instead, Propositions 1 to 3 and our remarks on time will help us to understand why these models work, what are their domains of validity, how their consistent integration can be achieved, and how their interpretation can be improved.

With QT and GR, we attempt to consistently model information about  $\mathscr{W}$ , represented in  $\mathscr{R}$ , as matter fields and quasi-classical, locally Minkowskian geometry on (3+1)-dimensional spacetime. However, the geometry and matter inferred from present knowledge are necessarily uncertain and coarse-grained — their specific forms have meaning only to the extent warranted by the information in  $\mathscr{R}$  to which we have access. This accessible information is redundantly encoded in the geometry and field configurations [7, 8, 9, 10], including in the physical representation of intellectual records (writing, etc.). Individual observations and present quantum states gain meaning only through reference to the reliably persistent, quasi-classical universe.

One might be tempted to identify  $\mathscr{W}$  as the global quantum state  $|\Psi\rangle$  of the cosmos, in the Heisenberg representation. But QT cannot then tell us how to factor  $|\Psi\rangle$  into the perceived quasi-classical environment and distinguished quantum subspaces (particles, spins, etc.). If we assume that QT applies universally and contemplate arbitrarily large subspaces (incorporating apparatus, laboratory, planet, etc.), then eventually we will reach a bound beyond which the remaining quasi-classical records hold insufficient information to fully determine the quantum state. That bound will define a limit to the applicability of quantum theory.

Only quantum state reduction allows us to accumulate information over time. To preserve newly acquired information, state reduction must directly increase the Kolmogorov complexity [11] of the quasi-classical universe in terms of which the reduced quantum state is defined. This will also make our model more fine grained. It follows that, contrary to conventional QT, the Hilbert space of quantum states must steadily grow.

Unable to predict what new information will actually be discovered about the world, QT covers all bets by giving unbiased treatment to all possibilities consistent with the present. But since the universe must always be self-consistent, each hypothetical future must have mutually consistent matter and geometry. The uncertain future of geometry must be held in lock-step with that of matter.

## 5 THE STRUCTURE OF THE WORLD

Although the world is beyond direct perception, we might still infer its generic structure and make testable predictions that confirm or deny the inferred structure. As a plausible example, we consider the following [12]:

**Conjecture (Topoverse):** *The world is a unique, connected, smooth 4-manifold,  $\mathcal{T}$ , with unconstrained global connectivity but no inherent geometry, fields, or other decoration.*

Although  $\mathcal{T} \equiv \mathcal{W}$ , we shall call  $\mathcal{T}$  the *topoverse* to emphasize its topological nature. Points and local neighbourhoods in  $\mathcal{T}$ , being all equivalent, contribute no information to perceived reality. However, the non-local, relational information residing in the global structure of  $\mathcal{T}$  is unbounded. By Proposition 2, perceived reality is an emerging representation of this global topology.

Proposals that complex 4-manifold topology is relevant to physics have a long history, originating with consideration of quantum fluctuations in spacetime geometry at the Planck scale. Wheeler imagined that exciton-like superpositions involving many different topologies could give particles [13]. Not satisfied with fluctuating geometry driving topology changes, he envisioned some unknown *pregeometry* from which the geometrical universe would emerge. References to many proposals regarding pregeometry are provided by Gibbs [14]. Sums over topologies are invoked in some approaches to loop quantum gravity and spin foams [15], but still within a geometrical framework. This *baking in* of the geometrical character of space and/or time that will eventually emerge is a common theme [16] — true pregeometry is elusive.

Novel features of the current proposal are: (i)  $\mathcal{T}$  is unique, whereas other models consider Feynman sums over all or large classes of 4-manifold topologies [15, 17]; (ii) the global connectivity of  $\mathcal{T}$  serves as the foundation for all information, whereas other models invoke additional structure, such as geometry, fields, group representations or causal structure, while often ignoring the topological information; and (iii) quantum theory does not apply to  $\mathcal{T}$ , but characterizes the emergent representations  $\mathcal{R}$  of  $\mathcal{T}$ .

Our conjecture, above, is motivated by the following construction of a representation of  $\mathcal{T}$  with striking, if simplistic, resemblance to a Feynman graph: Assign an arbitrary Riemannian metric to  $\mathcal{T}$  and pick any point  $x$ . Construct the 3-surfaces  $\Sigma_r$  whose points have the minimum metric distance  $r$  from  $x$ . Almost every  $\Sigma_r$  will be a compact 3-manifold whose topology can be uniquely expressed as a connected sum of a finite number of prime summands [18]. (While the sphere, torus and projective sphere are the only prime 2-manifolds, there is a countably infinite variety of prime 3-manifolds characterized by orientability, spinority, chirality and other properties [19].) Adjust the geometry so that the prime objects are small compared to their separations. As  $r$  increases,  $\Sigma_r$  will pass through critical levels at which the topology changes. These changes are elementary 3-manifold cobordisms involving only a small number of prime summands. The result is a graph-like structure with labeled edges (prime summands) and unlabeled vertices (cobordisms). The metric is no longer needed.

This construction suggests a correspondence of prime 3-manifolds (or equivalence classes thereof) to particle fields, and of elementary cobordisms to field interactions — particles and their interactions arise from pure topology. QT and GR provide the mathematical framework through which the simplistic correspondence is transformed into a time-space-matter representation of  $\mathcal{T}$ . The graph that is  $\mathcal{T}$  corresponds to pregeometric, *bare* or *virtual* particles. A sufficiently coarse-grained view of the graph yields the emergent geometry and field representation,  $\mathcal{R}$ , with the mutually-consistent properties of the *dressed* or *physical* matter we perceive. Quantum states are global and nonlocal because they must model the representation in  $\mathcal{R}$  of information about  $\mathcal{T}$  as a whole, rather than information about some localized portion of  $\mathcal{T}$ . Anything not interconnected with us would be beyond perception and thus not part of our reality.



## 6 DISCUSSION

We have cast the unique, atemporal world,  $\mathcal{W}$ , as the information source underlying perceived reality,  $\mathcal{R}$ . The process of emergence of  $\mathcal{R}$  corresponds to the advance of time. Time is also expressed in the entangled relations of records that comprise perceived reality. We exist within  $\mathcal{R}$  — always perceiving it as our present. We invent the past to enable our efficient compression of information in mental and theoretical models for  $\mathcal{R}$ . Since information always accumulates, the past must begin with zero information, zero entropy, and no records: no spacetime, no matter. The Big Bang thus represents the birth of spacetime geometry — albeit extremely coarse-grained and uncertain — and the first representation of information about  $\mathcal{W}$  as matter. To maintain consistency and respect entanglement, macroscopic features of the universe must evolve deterministically according to classical laws including GR.

All possible futures must be consistent with the present; but unlike the Many Worlds Interpretation of quantum mechanics, most of these hypothetical futures can never be realized due to incompatibility with  $\mathcal{W}$ . Nonetheless, many futures will be compatible with  $\mathcal{W}$ . We can thus imagine *many representations*: universes in which information about  $\mathcal{W}$  is incorporated in different orders. Although highly constrained by  $\mathcal{W}$ , these representations will be guided by the free will of their cognitive inhabitants who may formulate theories, conduct experiments, write essays, and so on.

QT allows us to model perceived reality using a continuum spacetime even though we have only finite information about  $\mathcal{W}$  to encode in observable quantum subspaces. QT also allows us to assign probabilities to the ways in which potential new information could combine with present information to shape our future reality. The actual new information will depend on  $\mathcal{W}$ . That it is definite should not be a surprise; the various alternatives allowed by QT are just an expression of our unavoidable ignorance.

To the extent they gain meaning from records, quantum subspaces will be perceived to interact with geometry. Semi-classical coupling will adequately describe their relation to the geometry (and other quasi-classical descriptors) of the present and near past. Predicting future geometry is more problematic, since a unitarily evolved quantum state cannot tell us which one of the many potential futures will actually occur. Whatever future we do perceive will have definite, but still coarse-grained, mutually compatible geometry and quasi-classical records. The compatibility requirement means that spacetime geometry cannot have quantum degrees of freedom independent of the matter degrees of freedom; uncertainty of future geometry arises solely from the uncertain quantum behaviour of matter.

Inspired by Wheeler's pregeometry, we have conjectured that the world is a 4-manifold,  $\mathcal{T}$  (the topoverse), with unconstrained global connectivity but no geometry or other decoration. A graphical representation of  $\mathcal{T}$ , whose edges correspond to prime 3-manifolds (the particle fields) and vertices to elementary cobordisms (field interactions), can be thought of as the complete Feynman graph of the universe for all time. Classification and characterization of the prime 3-manifolds and determination of their elementary cobordisms should reveal exact and approximate symmetries that can be placed into correspondence with Standard Model particles.

The universe is our personal and collective consistent representation of information about the world. It remains a puzzle how the willful acts of one observer can affect the

futures of all observers. Perhaps our cognitive perception is also entangled, and our individuality is an illusion. One might then say that the universe is alive, and we are its neurons.

## 7 ACKNOWLEDGEMENTS

I thank Harvey Brown, Olaf Dreyer, Stephen Green, John Moffat and Hans Westman for helpful discussions and feedback. I am grateful to the Perimeter Institute for hospitality.

## References

- [1] John O’Keefe and Lynn Nadel. *The Hippocampus as a Cognitive Map*. Clarendon Press, Oxford, (1978).
- [2] George F.R. Ellis. *Gen. Relativ. Gravit.*, **38**:1797–1824, (2006).
- [3] C.J. Isham. Canonical quantum gravity and the problem of time. In *Integral Systems, Quantum Groups, and Quantum Field Theories.*, eds. L. Ibort and M. Rodriguez, Kluwer, Dordrecht, pp. 157–207, (1993).
- [4] J. Butterfield and C.J. Isham. On the emergence of time in quantum gravity. In J. Butterfield, editor, *The Arguments of Time*, pages 111–168. Oxford University Press, (1999).
- [5] Ofer Lahav and Andrew R. Liddle. *J. Phys. G*, **33**:1, (2006).
- [6] Giulio Ruffini. Information, complexity, brains and reality (Kolmogorov Manifesto), (2007). arXiv:0704.1147v1 [physics.gen-ph].
- [7] Robin Blume-Kohout and W.H. Zurek. *Phys. Rev. A*, **73**:062310, (2006).
- [8] Harold Ollivier, David Poulin and Wojciech H. Zurek. *Phys. Rev. A*, **72**:042113, (2005).
- [9] Wojciech Hubert Zurek. Relative states and the environment: Einselection, enviance, quantum darwinism, and the existential interpretation, (2007). arXiv:0707.2832 [quant-ph].
- [10] Wojciech H. Zurek. *Rev. Mod. Phys.*, **75**:715, (2003).
- [11] Ming Li and Paul M.B. Vitanyi. *An Introduction to Kolmogorov Complexity and Its Applications*. Springer-Verlag, Berlin, (1993).
- [12] Martin A. Green. *Space-time structure and the origin of physical law*. PhD thesis, University of Toronto, (1980).
- [13] J.A. Wheeler. *Ann. Phys. (N.Y.)*, **2**:604, (1957).
- [14] Phil Gibbs. The small scale structure of space-time: a bibliographical review, (1995). arXiv:hep-th/9506171 v2.
- [15] M.P. Reisenberger and C. Rovelli. *Class. Quant. Grav.*, **18**(1):121–40, (2001).
- [16] Diego Meschini, Markku Lehto and Johanna Piilonen. *Stud. Hist. Philos. Mod. Phys.*, **36**:435–464, (2005).
- [17] S.W. Hawking. *Nucl. Phys.*, **B144**:349–362, (1978).
- [18] John Hempel. *3-manifolds*. Princeton University Press, (1976).
- [19] D. Giulini. *Int. J. Theor. Phys.*, **33**(4):913–30, (1994).